IGEX-98 Workshop

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Abstracts

SESSION: INTRODUCTION, OVERVIEW, AND GLONASS OPERATIONS

The GLONASS IGEX-98 Campaign: From Its Genesis to Its Realization

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In October 1998 a worldwide GLONASS observation campaign, named IGEX-98, was organized and is in fact still continuing. First of all some specifications were written by a Steering Committee, leading to an international call for participation followed by many proposals. Several groups have been very active in providing geodetic observations (GLONASS, GPS, SLR) and in analyzing these data for different purposes (precise orbit estimations, point positioning, clock comparisons, etc.). In total, 67 GLONASS receivers were installed worldwide (including 47 dual-frequency GLONASS geodetic receivers). All GLONASS receivers were co-located with GPS receivers (if not already dual GLONASS/GPS receivers). Many of these sites are also in co-location with other techniques (VLBI, SLR, DORIS, PRARE). The purpose of this paper is to present the scientific goals that led to organize such a large experiment and also to present the organization of this campaign giving a general overview of the research activity.

GLONASS Operational Status and Plans

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<<No abstract available>>

GLONASS Constellation Maintenance, 1998-1999

Gerald Cook, *Sequoia Research Corporation, Torrance, CA, USA*

Amid troubled economic and political times, the Russians have struggled to maintain a useable constellation of satellites. The outlook for the GLONASS constellation seemed very bleak at ION-GPS 98. Over a three year span without launches, the number of useable satellites dwindled to eleven. Ailing satellites were kept on board even when very unreliable. However, 1999 has seen introduction of three satellites launched at the end of 1998, a long awaited activation of the spare satellite in plane 2, and more recent efforts to revitalize another existing satellite long thought dead. This paper examines some of the maintenance problems noted during the last 1.5 years and some of the success stories. Individual and historical satellite accuracies are examined to determine how well the new satellites are doing.

GLONASS and the International Terrestrial Reference System

Claude Boucher, *Institut Géographique National, Marne-la-Vallee, France*

The first results of the IGEX-98 campaign provide significant materials to illustrate the mutual benefits of the GLONASS system and the realization of the International Terrestrial Reference System (ITRS). This paper reviews the various relations and their synergy with the GPS system, especially in the frame of the International GPS Service (IGS). Three points are particularly discussed:

- results of the IGEX-98 for terrestrial reference frame
- possible inclusion of GLONASS as a new technique for the realization of the ITRS by the International Earth Rotation Service (IERS)
- GLONASS as an active realization of the ITRS, in conjunction with GPS or the planned Galileo system.

SESSION: RECEIVER TECHNOLOGY

An Operational Evaluation of the JPS Legacy Receiver

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Based on cost, performance specifications, and availability the University of Florida (UF) selected the Javad Positioning System (JPS) Legacy GLONASS/GPS receiver to participate in the IGEX Campaign. The IGEX designation assigned to the UF station is GATR. The JPS antenna was mounted on a 1.3 m high by 0.1 m diameter cast iron pipe pillar, on the roof of Reed Laboratory, on the UF Gainesville campus. The pillar is one of three on the roof, all of which are within a few meters of station Bolt, a station in the National Geodetic Survey's GPS-based Florida High Accuracy Reference Network (HARN). Station Bolt has been used for several UF research programs within the past few years and accurate coordinates in the ITRF were already known before the IGEX campaign began. The antenna was connected by a 25 m long co-axial cable to the receiver, which was located in an environmentally controlled room one floor below. The observational data collected were transferred to a personal computer for storage and quality checking, and then sent in 24-hour blocks by FTP to the NASA CDDIS, daily.

Installation of the JPS receiver took only minutes, and the system began collecting observations on all visible GPS and GLONASS satellites immediately. However, a number of problems materialized within the first few weeks of operation, requiring consultations with the manufacturer's technical staff, and the installation of several upgraded versions of the firmware. Since this initial shake down period, the receiver has worked reliably for more than six months continuously in the hot humid weather of central Florida. There have been no failures of the electronic components. Statistical summaries of the data collected, operational difficulties, and explanations for specific gaps in the data will be presented. Based on computations performed by UF personnel and by others analyzing the IGEX data set, the data have been of acceptable quality.

ESA/ISN Dual-Frequency GPS/GLONASS Receiver

G. Brodin, D. Lowe, P. Daly, *University of Leeds, Leeds, UK*; P. Silvestrin, T. Martin-Mur, I. Romero, J. Dow, *European Space Agency, Darmstadt, Germany*

In this paper the architecture, configuration and performance of the ESA/ISN combined dual-frequency GPS/GLONASS receiver used in the IGEX-98 campaign are presented. The receiver is a high performance breadboard unit developed by the Institute of Satellite Navigation (ISN), University of Leeds, UK for the European Space Agency (ESA), and is the only European dual-frequency GPS/GLONASS receiver to have taken part in the campaign. The laboratory-based breadboard has operated on a near-continuous basis for the duration of IGEX-98 and beyond, collecting primarily dual-frequency GLONASS data, with dual-frequency GPS data collected on a secondary basis for comparative purposes. The IGEX campaign has been the final testing ground for the ESA/ISN receiver, providing the prefect opportunity to thoroughly validate the operation of its dual-frequency GLONASS carrier phase tracking. This opportunity has been timely as a radiation-tolerant ASIC largely based on the digital hardware designed and developed at the ISN has been produced by ESA and is planned to become available to the European GNSS community. The ASIC will be used in a number of future space missions by ESA dedicated to atmospheric sounding by radio occultation. The validation of the performance of the receiver prior to completion of the ASIC has been an essential part of the work carried out by the ISN for ESA during the last year. This validation is now considered to have been successfully concluded, a fact endorsed through the results of the data centers active during the IGEX-98 campaign that have processed the data produced by the ESA/ISN receiver. The ESA/ISN receiver has contributed high quality dual-frequency GLONASS carrier phase data to the IGEX campaign, a contribution that will aid the analysis of the GLONASS system.

This paper will be split into two main sections: first, the receiver architecture will be presented along with a description of the configuration that was employed during the campaign. The measurement precision and other salient parameters that have been achieved by the receiver during its development will be presented. Secondly, the performance of the receiver as determined by the independent data processing centers that took part in the IGEX campaign shall be compiled and analyzed. This data indicates the accuracy and repeatability that has been achieved by the receiver in the configuration used for the campaign. Results to date from the data processing centers indicate that the receiver has consistently performed to a high standard, its measurement accuracy being similar to other dual-frequency GPS/GLONASS units. Additional processing of the ESA/ISN receiver data shall be carried out by ESA at ESOC to gain further insight into the receiver performance and will be included in the paper.

An Analysis of Dual-Frequency Receivers used in the IGEX-98 Campaign
B. Wiley, *National Imagery and Mapping Agency, St. Louis, MO, USA*

This paper describes the analysis of receivers used during the IGEX-98 campaign. Dual-frequency receivers with the capability of tracking both GPS and GLONASS are the primary focus. Most of the dual-frequency receivers being used in the campaign are either R-100 receivers manufactured by 3S Navigation or Z18 receivers manufactured by Ashtech. Data produced for the campaign are used for the analysis. Data from BKG showing GLONASS/GPS time offset was considered. Data from GFZ showing the bias and repeatability of station coordinates was considered. The User Range Error (URE) is calculated for R-100 receivers. A discussion of each station's URE values is given. An in-depth analysis of the performance of the Santiago site is made. The GFZ data indicate that for computation of station coordinates, particular sites have a larger bias and rms. These sites are mainly those with R-100 receivers. However, other types of receivers also show a large bias and rms for particular stations. Additionally, other sites with R-100 receivers show small biases and rms values. The URE computation for R-100 receivers typically shows a value of less than ten meters. A relationship between receiver operations and the analysis center processing schema and resulting errors is investigated.

SESSION: NETWORK OPERATIONS

IGEX Network and Data Processing Organization
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The paper discusses the organization of the IGEX-98 network: The guidelines for stations and data collection, the data flow from the receivers to the data centers to the analysis centers, the available information about the tracking sites, and the current relationship with IGS and ILRS. (During the official duration of the campaign, the International Laser Tracking Service intensified its GLONASS tracking on request of the IGEX Steering Committee).

IGEX-98 Data Flow
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The Crustal Dynamics Data Information System (CDDIS) served as a global data center for the IGEX-98. This activity was a logical extension of the support the CDDIS provides to the IGS. However, we found that the data sets supplied for IGEX had many more problems than we have found in recent years supporting the IGS. This presentation will discuss the data flow utilized for IGEX-98, data latency, and the various problems that were found and their impact on the service as a whole.

BKG's Operation of GPS/GLONASS Receivers and Its Regional IGEX Data Center
H. Habrich, *Bundesamt fuer Kartographie und Geodaesie, Frankfurt, Germany*

The Bundesamt fuer Kartographie und Geodaesie (BKG) owns six dual-frequency combined GPS/GLONASS receivers, in detail four Ashtech Z-18 and two 3S Navigation R-100. Four of these receivers were at least partly operated during the IGEX campaign.

Two Ashtech Z-18s are permanently operating in Wettzell (Germany) and Reykjavik (Iceland). They are connected to a PC with an Internet connection, that is running the "GPS-Base" software from the Terrasat company. A fully automated data flow comparable to that used within IGS was established. By reason of the additional GLONASS satellites, the size of the observation files is bigger compared to files from IGS stations. This was recognized in the duration of the file transfer, but was not critical. The two 3S Navigation R-100 receivers were set up in Wettzell and

Ankara (Turkey) at the beginning of the IGEX campaign. Due to the lack of remote control capabilities for the receiver and communications to the site, the receiver in Ankara was shipped to BKG for maintenance after a short period in IGEX.

A regional IGEX data center was established at BKG parallel to the existing IGS data center. Specific problems for some stations occurred if the RINEX format definition for the file headers and the file names were not correctly considered. The RINEX compact format was successfully used for combined GPS/GLONASS observation files. Special actions were required, because the compressed files from some stations could not be decompressed on our UNIX system. These files were compressed with, for example, the “gzip” program. All IGEX data files were uploaded to the global data center at IGN. Statistics with data holdings and latencies are presented.

Integrity Monitoring Software for GPS/GLONASS Reference Stations
K. de Jong, *Delft University of Technology, Delft, The Netherlands*

Delft University of Technology (DUT) has traditionally been involved in research towards quality control of (geodetic) observations. Originally applied to conventional surveying techniques, the quality control procedures developed at DUT are also utilized within the context of the Dutch permanent GPS array. The dual-frequency GPS receivers at the reference stations of the array all employ dedicated integrity monitoring software based on DUT’s quality control theory, to insure the quality and reliability of their observations. Recently, in view of the participation of the DUT in the IGEX-98 campaign, this integrity monitoring software has been extended to incorporate dual-frequency GLONASS observations as well as GPS observations.

The integrity monitoring software aims to detect anomalies in the GLONASS/GPS data in real time. To that end, the software employs a recursive Kalman filter and DUT’s recursive DIA (Detection, Identification and Adaption) validation procedure. As the software does not require any external information, like satellite and receiver positions, velocities and clock behavior or information on the atmospheric effects, it can be executed independent of the application for which the data was originally collected. The software is able to detect slips of one cycle in the carrier data in real time, even for relatively long observation intervals of 30 seconds. Moreover, as a by-product, the software also produces precise estimates of the absolute ionospheric delay. It could therefore be a valuable pre-processor for IGEX and IGS GPS and GLONASS observations.

The DUT integrity monitoring software is freely available for the scientific community. It is written in standard ANSI C and can therefore be compiled and run on any operating system. In this presentation, some of the features of the software are highlighted, together with processing results from the dual-frequency GPS/GLONASS receiver at the Delft IGEX station.

SESSION: TIME AND TIME TRANSFER

Recent Progress in Time Metrology and a Role for GLONASS
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For one and a half decades the American Global Positioning System (GPS) has served the principal needs of national timing laboratories for regular comparisons of remote atomic clocks. In the pre-GPS era the technology of atomic clocks was always ahead of that of time transfer. The introduction of GPS has led to a major improvement of worldwide time metrology in precision, accuracy and coverage. With GPS C/A-code, time comparisons are performed with an uncertainty of a few nanoseconds for short baselines (up to 1000 km) and several nanoseconds for intercontinental distances, even if voluntary degradation of the system, known as Selective Availability (SA), is activated.

In many ways the Russian Global Orbiting Navigation Satellite System (GLONASS) is similar to the GPS but, until recently, it was rarely used by the international time metrology community because no suitable receivers were available commercially. This situation is now changing and the first permanent international time links have been established. The performance of GLONASS C/A-code common-view time transfer is similar to that of GPS C/A-code.

The performance of single-channel GPS and GLONASS C/A-code common-view time transfer, with an uncertainty of about 3 ns (one part in 10^{14} for averaging times of a few days), is however barely sufficient for the comparison of today's atomic clocks and needs to be improved rapidly to meet the challenge of the clocks currently being designed. For this reason the timing community is engaged in the development of new approaches to time and frequency comparisons. Among them are techniques based on multi-channel GPS and GLONASS C/A-code measurements, GLONASS P-code measurements, GPS carrier-phase measurements, temperature-stabilized antennas, standardization of receiver software and two-way time transfer through telecommunication satellites.

Some tests of the GLONASS P-code during a one-site comparison show that, for single-channel GLONASS P-code time and frequency transfer, a stability of 2 parts in 10^{15} is obtained over one day (200 picoseconds/day). These results indicate that GLONASS P-code time and frequency transfer in multi-channel mode should reach at least a stability of 1 part in 10^{15} over one day (100 picoseconds/day) for short baselines.

The GPS and GLONASS are also outstanding tools for the dissemination of Coordinated Universal Time (UTC). As GLONASS is not affected by Selective Availability (SA) this presents some advantages.

An Experiment of Transatlantic GLONASS P-Code Time Transfer Using IGEX Precise Ephemerides

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GLONASS P-code has two main advantages for precision time synchronization. First, GLONASS P-code chip length is one-tenth that of GLONASS C/A-code and about one-fifth that of GPS C/A-code. This allows GLONASS P-code pseudo-range measurements to be considerably more precise than comparable GPS or GLONASS C/A-code measurements. Second, GLONASS P-code is transmitted on both L1 and L2 frequencies, without Anti-Spoofing (AS) encryption. The absence of AS encryption allows GLONASS P-code measurements to be used for high-precision ionospheric measurements.

GLONASS data are subject to a receiver bias which may be different for each GLONASS frequency. The spread of these biases across satellites can reach 15 nanoseconds and may therefore mask other noise sources. Based on the data available so far, GLONASS frequency biases appear to be a function of temperature and relate to specific receivers. Once calibrated with respect to a reference receiver, however, the values remain almost constant provided that the temperature does not change. They can therefore be compensated for in the software.

In this paper we describe a test of long-distance time transfer using GLONASS P-code common-view measurements between some North American time laboratories and some European time laboratories. Temperature-stabilized antennas were used on both continents and GLONASS frequency biases were determined by means of a portable reference receiver. Dual-frequency GLONASS P-code ionospheric measurements combined with IGEX GLONASS precise ephemerides provided the best conditions for this test.

Computation of GLONASS Precise Ephemerides For International Time Transfer

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Precise orbits for the GLONASS satellite system have been computed within the framework of the IGEX (International GLONASS Experiment) campaign, using the orbital system TOP. Only the phase and code data from dual-frequency receivers were used. The paper presents the mathematical model used for the calculations of the satellite orbits, the clock parameters, and the coordinates of the stations participating in IGEX. A comparison of the data collected each week is presented. The dependence of the accuracy of the satellite orbit on the length of the arc is discussed. One of the main objectives of this work is the application of the precise ephemerides to long-distance common-view time transfer using GLONASS satellites. For this reason orbits are computed for the middle of satellite standard common-view tracks, to avoid interpolation.

The application of precise orbits in place of the broadcast ones, as well as the use of a precise ionospheric model, or ionospheric measurements, should result in a reduction of the uncertainty of intercontinental clock comparisons to the one nanosecond level.

Dual-Frequency GLONASS Measurements and Their Impact on Ionospheric Compensation for Precise Time Transfer Applications

J. Beser, *3S Navigation, Irvine, CA, USA*

The absence of anti-spoofing on GLONASS allows the generation of dual-frequency P-code measurements. These, in turn, provide for the computation and compensation of the ionospheric delay from the pseudorange observables.

This real time measurement is potentially more accurate than estimated delays based on a modeled ionosphere and this enhanced accuracy is even more pronounced in the current solar max period.

Care must be taken, however, if the full benefits are to be gained from these dual-frequency measurements. L1 versus L2 as well as inter-satellite (i.e., inter-frequency) biases as a function of temperature must be carefully calibrated. This is not an easy undertaking and is probably the biggest remaining hurdle to the universal acceptance of GLONASS for precise time transfer applications.

These calibration issues will be addressed, and results will be presented comparing real time dual-frequency-derived ionospheric measurements with post-mission delays computed from NASA's global TEC data base for the same period.

SESSION: ORBIT DETERMINATION

Results of CODE as an Analysis Center of the IGEX-98 Campaign

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On October 19, 1998, the beginning of the International GLONASS Experiment (IGEX-98), the Center for Orbit Determination in Europe (CODE) started to compute precise orbits for all active GLONASS satellites. Due to the repeated extension of the campaign, results covering a time span of about 40 weeks will be ready to be presented at the IGEX-98 Workshop.

Data processing of the IGEX-98 campaign is done on a routine basis at CODE and the precise GLONASS ephemerides are made available through the global IGEX-98 data centers. The improved GLONASS orbits are referred to the International Terrestrial Reference System (ITRF96) and to GPS system time. CODE GLONASS orbits are therefore fully compatible with CODE GPS orbits and allow a combined processing of both, the GPS and the GLONASS satellite system. For the GLONASS orbit determination, the GPS orbits and the Earth rotation parameters are fixed to the CODE's final IGS solution. Six initial conditions and nine radiation pressure parameters are set up for each satellite and the final results stem from the middle day of a 5-day arc. The quality of the precise GLONASS orbits is assessed in the following two ways:

- The internal consistency is checked by looking at the orbit overlaps at the day boundaries and by fitting a seven-day arc through the final daily solutions.
- The tracking of GLONASS satellites by the SLR community allows an independent evaluation of the accuracy of the computed GLONASS orbits. Comparisons of CODE's GLONASS orbits with the SLR measurements prove that the achieved accuracy is of the order of 20cm. This corresponds to an improvement by a factor of ten with respect to the broadcast orbit accuracy.

Furthermore, for a few weeks, the IGEX network solutions were combined with those of the IGS network. Earth rotation parameters and orbit parameters for both, GPS and GLONASS satellites, were simultaneously determined in this case.

IGEX Analysis at BKG

H. Habrich, *Bundesamt fuer Kartographie und Geodaesie, Frankfurt, Germany*

The Bundesamt fuer Kartographie und Geodasie (BKG) takes part in the IGEX campaign with the operation of currently three dual-frequency combined GPS/GLONASS receivers, the establishment of a regional IGEX data center and the analysis of IGEX observations. Furthermore SLR observations to GLONASS satellites were performed at the observatory in Wettzell and analyzed at BKG. This presentation deals with the analysis of observations from combined GPS/GLONASS receivers.

In collaboration with the Astronomical Institute, University of Berne (AIUB), the Bernese GPS Software was modified for a combined GPS/GLONASS processing. The new software allows the estimations of, for example, orbit parameters of GLONASS satellites and also ambiguity resolution on long baselines, by applying successively the wide-lane and narrow-lane linear combination approach. However the ambiguity resolution is not yet implemented into the routine processing scheme.

With the beginning of the IGEX campaign in October 1998, a weekly summary file of the processing results was submitted by IGEXMail. The analysis at BKG is specified by the following steps: (1) A code single point solution is determined for each processed station in order to estimate receiver clock values and, in the case of combined GPS/GLONASS observations, the system time difference between GPS and GLONASS. The estimates of the system time difference show a formal error of approximately 1 nsec. The estimated values differ for up to 1 microsecond, depending on the receiver type; (2) a baseline-wise pre-processing of the phase observations determines the relative receiver clocks of the two receivers for each epoch and corrects the cycle slips on the single difference level. A new ambiguity parameter is set up, if a cycle slip can not be corrected; (3) GLONASS orbit parameters are determined in the processing of double difference phase observations of GPS and GLONASS satellites. Also, differences between GPS and GLONASS satellites are formed. The IGS orbits and Earth rotation parameters are fixed, as well as the broadcasted values for GLONASS satellite clocks. For selected stations the corresponding ITRF-96 coordinates are tightly constrained. The middle day of a three-day arc is used for daily orbit results. A comparison of the satellite positions of the daily results to a seven-day arc yields rms values of 10 to 20 cm for well defined GLONASS satellites. (4) A Helmert transformation between the GLONASS broadcast orbits given in PZ-90 and the new precise orbits in ITRF-96 provides a set of transformation parameters between the two systems and is calculated for every day. The estimates confirm a significant rotation around the z-axis between the two systems

The presentation includes a detailed description of the processing scheme, problems experienced, and a summary of the results for the processed period.

GLONASS Data Analysis at ESA/ESOC

T.J. Martin-Mur, J.M. Dow, C. Garcia, I. Romero, *European Space Agency, Darmstadt, Germany;* P. Daly, *University of Leeds, Leeds, UK;* P. Silvestrin, *European Space Agency, Darmstadt, Germany*

This paper presents the GLONASS analysis activities performed at ESOC in the context of a joint proposal of ESA/ESOC, University of Leeds, and ESA/ESTEC for the IGEX-98 campaign. ESOC has been for a long time committed to the processing and analysis of GNSS data for precise orbit determination. Our GNSS activities started in 1991 with the analysis of the data from the GPS CIGNET-91 campaign and the software for automated processing of GNSS data has been almost constantly improved and extended since then. The processing of GLONASS data has benefited from ESOC experience as an IGS Analysis Center but has needed a number of GLONASS specific adaptations for the software.

The processing strategy has been considerably changed to adapt to the objectives of the IGEX campaign. The most important innovation with respect to our IGS strategy is the use of the undifferenced carrier phase and pseudorange as basic observables instead of double differences. This represents an improvement mainly in three aspects. First, the satellite and receiver clock biases can be more accurately estimated along with the orbits in a way that makes them consistent to each other. Second, more data from the GLONASS satellites can be used when it is not necessary to perform double differences. This is important if we take into account the scarcity of the IGEX network. Third, the assessment of individual GLONASS receivers can be much accurately characterized with this approach.

The orbit determination software BAHN was modified to add the capability to estimate time dependent parameters, typically receiver and satellite clock biases. This was imperative in order to be able to process undifferenced data. The lack of a priori solar radiation pressure models for the GLONASS satellites made also necessary the development and implementation of appropriate empirical force models.

Our processing strategy is based on the simultaneous processing of GPS and GLONASS data from all IGEX receivers with dual-frequency GLONASS data and a number of core IGS stations. GPS orbits and clocks are tightly constrained to the ESOC IGS final solutions and IGS station coordinates are fixed to ITRF values. This combined processing requires the estimation of inter-system biases for those receivers that provide dual-frequency GPS and GLONASS data.

One important objective of IGEX is to produce a set of GLONASS station coordinates consistent with the ITRF. We have produced station coordinate and EOP solutions in SINEX format for IGEX and IGS stations that can be used to link the IGEX network to the ITRF.

The paper will analyze the current ESOC IGEX processing along with an evaluation of the results of the first months of processing.

Determination of GLONASS Satellite Orbits at JPL — Approach and Results

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Based on the software (GIPSY/OASIS) used for and products generated from IGS data processing at JPL, a strategy is developed to process the IGEX data and determine the orbits of GLONASS satellites. Our approach processes undifferenced dual-frequency pseudorange and carrier phase data. The process is divided into two steps. First, the station locations and receiver clocks of those sites that track GPS satellites are precisely determined by fixing the GPS satellite orbits and clocks to the IGS solution produced at JPL. In the second step, the GLONASS satellite orbits are determined with GLONASS tracking data with those stations in the GPS-defined system serving as fiducial sites. For the stations that track both GPS and GLONASS satellites, a random walk bias between the clocks of GPS tracking and GLONASS tracking is estimated. For the stations that track GLONASS satellites only, receiver clocks are estimated as white noise. Random walk troposphere zenith delays are estimated for all the stations.

IGEX data is processed with this approach and orbit precision is evaluated through orbit overlapping error, as well as comparison with solutions of other institutions. With an orbit arc as short as 30 hours, and estimating only 8 standard GPS-type orbit parameters for each satellite, the precision of our orbit solution is at the 50 cm level. With a longer orbit arc and estimating more accommodating orbit model parameters, 30 cm orbit precision can be achieved.

A by-product, the transformation between the ITRF reference system and the PZ-90 reference system, is obtained by comparing the precise orbit solution (in ITRF) and the broadcast orbit (in PZ-90) in an Earth-fixed system.

Determination of Precise Ephemeris Data of GLONASS Satellites in PZ-90 Coordinate System

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Based on observations made in the frames of IGEX-98, the authors determined precise ephemeris data for GLONASS satellites in the PZ-90 coordinate system. They used measurements of Z-18 receivers (Magellan/Ashtech) located in five sites: three sites are located in Russia (Mendeleevo, Irkutsk, Khabarovsk), one site in Finland, and one site in Switzerland. The coordinates for the first three sites were obtained by transferring the coordinate data from PZ-90 reference sites. Coordinates for the foreign sites were obtained using WGS84-PZ90 transformation, and parameters of the transformation were earlier determined by the authors themselves and then published. In this case the errors of the transformation do not exceed 1 meter.

The paper discusses two methods of precise ephemeris determination. The first one is the traditional correction of orbital parameters (Keplerian orbital elements) using measurements on three-day intervals of observation. Numerical integration of equations of satellite motion counts gravitational field of Earth (a model of harmonic coefficients up to 8th degree), luni-solar effects, pressure of light, tide effects. The second method estimates possible offsets in ephemeris data via radial, binormal, and transversal constituents as a trigonometrical series. It is based on residual errors in measurements obtained on one-day intervals from the above mentioned five sites. This method does not use integration of the equations of satellite motion.

The paper provides results of GLONASS code and phase measurements. Detailed analysis of the results, including comparisons of broadcast and precise ephemeris data, is given. The authors compare their results obtained by both methods and ephemeris data obtained by other explorers in WGS-84. The results indicate that precise GLONASS satellite ephemerides are at the sub-meter level of accuracy, and application of phase measurements enables decimeter accuracy.

GLONASS Precise Orbits as a Result of the IGEX-98 Laser Tracking Campaign

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In the frame of the IGEX campaign, the laser group of the Russian Mission Control Center (MCC) implemented precise orbit determination of eight GLONASS satellites permanently tracked by world-wide distributed laser stations. Results of orbit determination represented in SP3 format and related to GPS time and ITRF94 are stored in CDDIS for the whole IGEX campaign.

The models used have been proved by MCC's experience in SLR data processing. They generally follow IERS recommendations with the exceptions for direct and reflected solar pressure models developed by MCC in 1995-96.

Orbits of all satellites are solved independently over eight-day arcs. Neighboring solutions are independent because every next arc starts exactly 8 days after the beginning of the previous one. Such a scheme allows monitoring of the accuracy of orbit determination by comparison of neighboring solutions. The approximate average expected accuracy 1RMS=1.0 - 1.5m and better is dependent on the GLONASS satellite and the amount of SLR tracking data.

There is detailed information concerning MCC SLR orbits of GLONASS satellites in comparison with "phase" orbits in radial, along-track and cross-track directions. Such post-processing of orbits based on measurements of different nature is extremely important for validation of the obtained results.

SLR GLONASS Orbit Determination

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The intense observation campaign during IGEX-98 provided a data set which could be used to compare and calibrate SLR- and microwave-determined GLONASS satellite orbits. Orbit determination of the GLONASS satellites was undertaken using the SLR data observed from October 1998 to April 1999. The resulting trajectories generated from this estimation process are compared to those produced by the IGS Analysis Centers using the microwave data. The results of these comparisons are presented and conclusions given in the form of lessons learned from the co-location of high precision space geodetic techniques, not only at the observing stations, but also at the spacecraft.

Comparison of Precise GLONASS Ephemerides Obtained from the IGEX Campaign

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The combination and evaluation of precise GLONASS ephemerides is a major task of the IGEX Analysis Center Coordinator. Currently daily orbit solutions, based both on microwave and laser tracking data, are available from five IGEX Analysis Centers. Even in late 1998 the orbit consistency of these data was approaching the 20 cm level. A combination of the Centers' ephemerides, additionally implying the advantage of improved reliability and precision, seemed to be feasible and desirable.

This paper describes the method used to calculate the combined IGEX orbits and discusses the quality of the solution.

Comparison of Precise SLR Orbits of the GLONASS Satellites with Microwave-based Orbits

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The main IGEX-98 campaign ran from 1998 October 1 until 1999 April 30, during which time a large number of precise laser range observations were made to the nine GLONASS satellites that were chosen as principal targets. One of the aims of the Campaign is to compare precise orbits derived from laser range observations with those generated operationally from the microwave observations, in order to make independent determinations of the accuracy of those operational orbits. In this paper we describe our methods of generating the SLR-based orbits, using in-house analysis software that has been used in a variety of other investigations. We find that in most cases there are sufficient numbers of SLR observations to compute reliable seven-day orbits which give post-fit range residual RMS values of about 6-10 cm. We then compare these orbits with the daily ephemerides of the satellites computed by the Centre for Orbit Determination in Europe (CODE). We resolve the differences between the orbits into the along-track, across-track and radial directions. The results imply an RMS agreement between SLR and the CODE orbits at a level of about one meter in along-track and across-track directions, and about 20 cm radially. There are indications of the systematic bias between the orbits in the along-track and radial directions, and we discuss possible causes of these. In particular the radial difference may be related to the center of mass correction for the laser retroreflector array, which itself may be ranging-system dependent.

SESSION: APPLICATIONS

IGEX – A Regional Analysis of Data from the Southern Hemisphere

M. Stewart, M. Tsakiri, J. Wang, J. Monico, *Curtin University of Technology, Perth, Australia*

This paper presents a regional treatment of data from the limited number of sites operating in the Southern Hemisphere as part of the International GLONASS EXperiment (IGEX). GLONASS only, GPS only and combined daily solutions for a network covering Australia, Antarctica and South America will be shown to demonstrate how the inclusion of GLONASS data can improve the overall quality of regional geodetic positioning in the Southern Hemisphere. The precision of IGEX precise ephemerides computed by BKG, CODE, ESA, and GFZ is also discussed in relation to the Southern Hemisphere baseline solutions. Finally, some comments are made regarding the processing strategies adopted in computing this preliminary IGEX solution.

Applications of Precise IGEX-98 Satellite Orbits in Medium-Range Fast Static and Kinematic GPS/GLONASS Positioning

J. Wang, M. Stewart, M. Tsakiri, T. Forward, *Curtin University of Technology, Perth, Australia*

Satellite-based navigation systems, GPS and GLONASS, have been playing an increasingly important role in precise geodetic surveys. For fast-static and kinematic GPS/GLONASS satellite positioning, integer carrier phase ambiguity resolution is essential. Reliable ambiguity resolution, however, is highly dependent on appropriately reducing or modeling systematic errors in the measurements, such as satellite orbital errors. In fast static or kinematic surveys, due to the weak positioning geometry, it is difficult to model satellite orbital errors in the positioning solution. As the baseline length is extended, the orbital errors in the measurements become more significant. Therefore, reducing the satellite orbital errors is the key to reliable ambiguity resolution and precise positioning for long baselines (>15km).

In this study, the precise IGEX-98 satellite orbits are used to improve the reliability of ambiguity resolution and the quality of positioning for medium-range (15-100km) static and kinematic applications. Several data sets collected using two GPS/GLONASS receivers are processed with the GPS/GLONASS ambiguity resolution method developed in Curtin University. The accuracy and reliability of the IGEX-98 satellite orbits from the different data analysis centers are demonstrated and compared in terms of their performances in ambiguity resolution for medium-range fast static and kinematic applications.

PZ-90 GLONASS to ITRF Transformation as a Result of the IGEX-98 Laser Tracking Campaign

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The ILRS Laser Analysis Center of the Russian Mission Control Center (MCC) implemented precise orbit determination of eight GLONASS satellites based on SLR data. Results of orbit determination represented in SP3 format and related to GPS time and ITRF94 are stored in CDDIS for the whole IGEX campaign.

These SLR-based orbits have been used to get a time dependent transformation matrix from ITRF94 (WGS84) to PZ-90 (GLONASS) represented by ephemeris data collected in the frame of IGEX. These results are compared to those reported at ION GPS-98.

The models and software generally follow IERS recommendations and were developed by MCC in 1995-98. In particular this software has been used in the work on the WGS 84 (ITRF94) to PZ-90 (GLONASS) transformation reported at ION GPS-98 in Nashville.

Information is presented concerning the original MCC SLR matrix based on the IGEX-98 campaign and in comparison with 1995-96 results. Such analysis based on measurements of different nature and independent software is extremely important for validation of the obtained results.

PZ-90/WGS 84 Transformation Parameters Directly from GLONASS Range Measurements

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Undoubtedly, the combined use of GPS and GLONASS brings along a number of advantages as compared to the use of either of the systems alone. However, GPS and GLONASS employ different coordinate frames to express satellite positions at a given time. To make full use of the combination, the transformation between these two frames must be known with sufficient accuracy. Until recently, however, the determination of this coordinate transformation was obstructed by the non-availability of known sites surveyed in PZ-90 and/or by the limited number of available GLONASS receivers. In the IGEX-98 campaign, for the first time a significant number of GLONASS receivers was operated simultaneously at observation sites all around the globe.

The parameters of the coordinate transformation between PZ-90 and WGS84 are conventionally determined by surveying sites in both coordinate frames and then comparing their coordinates. These sites can be located on the surface of the Earth (receiver locations) or in space (satellite locations).

This paper introduces a new method of determining the transformation parameters. Instead of surveying locations with known WGS84 coordinates in the PZ-90 frame and comparing these coordinates, the transformation parameters are estimated directly from range measurements to GLONASS satellites at known WGS84 observation sites. The derived transformation parameters are presented and compared to other estimations.

Transformation between PZ-90 and WGS 84

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There have been a number of independent attempts in the past five years to estimate a transformation between WGS 84 and PZ-90. These attempts, however, were constrained and limited by lack of precise GPS and GLONASS measurements from widely separated stations. IGEX-98 has remedied the situation; this paper presents an analysis based on the wealth of measurements from a global network of stations.

Our approach is the same as proposed and tried earlier by MIT Lincoln Laboratory: to compare position coordinates of GLONASS satellites expressed in the two coordinate frames. In the previous attempt, we had obtained precise ephemerides of several GLONASS satellites in WGS 84, but were limited to relatively coarse position estimates in PZ-90 broadcast by the satellites. The lack of availability of precise ephemerides in PZ-90 had remained the stumbling block in seeing this approach to its logical conclusion.

IGEX-98 has allowed computation of precise ephemerides of GLONASS satellites in both WGS 84 and in PZ-90. We estimate a transformation by relating the satellite positions expressed in the two coordinate frames via a seven-parameter transformation accounting for displacement of the origin, rotation of the axes, and a scale factor. We have found that a rotation of the *z*-axis brings the two coordinate frames substantially in coincidence, and reduces the residuals by over 95%. The role of the remaining parameters ranges from very small to insignificant. The estimated transformation is believed to provide to sub-meter accuracy. The analysis is continuing.

SESSION: FUTURE PLANS

The Future of IGEX-98

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The IGEX-98 started on October 19, 1998 and was officially terminated on April 19, 1999. Since that time IGEX activities continue on a "best effort basis" (details see IGEXMail no. 290). The achievements are remarkable. (1) A network of currently about 30 combined GLONASS/GPS dual-frequency receivers is tracking "all in view" GLONASS satellites on a routine basis. (2) The ILRS network was observing about 70% of the entire GLONASS constellation for the official duration of the campaign; afterwards a subset of the GLONASS was and is still tracked by the ILRS. (3) With a delay of about 10 weeks, ephemerides with an accuracy of 1-3 decimeters rms per satellite are available for each day since October 1998 from more than one IGEX Analysis Center. (4) Since GPS week 988, the orbits are compared by the IGEX coordinator and robust, combined orbits are available as well.

In view of these achievements and in view of the (potential) impact of the GLONASS on space geodetic work (e.g., on time and frequency transfer, or on spaceborne applications), the IGEX Steering Committee proposes to continue the precise GLONASS orbit and clock determination activities in the framework of an internationally coordinated pilot project. This implies continued observations from the IGEX ground tracking network.

Four important international organizations, namely CSTG, IERS, IGS, and ION (in alphabetic order) were conducting the IGEX-98 as a joint experiment. The project was chaired by the CSTG subcommission on "precise satellite microwave systems". The IGEX-98 is currently a working group of IGS.

In this paper we outline the possible structure and affiliation of the future scientific GLONASS tracking and data analysis service for the years 1999-2003. We propose in particular a leading organization and the liaison to the IGS. Technically, the procedure defined in the memorandum "IGS Policy for the Establishment of IGS Projects and Working Groups" (available through the IGS Central Bureau Information System) will be followed to establish the new organization.

The paper should be viewed as a position paper for the IGEX workshop, available through IGEX mail at least one week prior to the IGEX workshop. The paper contains draft resolutions to be discussed, modified, and (hopefully) accepted by the workshop participants. The final version of the paper should serve as the basis for the next four years of scientific GLONASS-related tracking and analysis activities.

IGEX-98 Workshop

Poster Abstracts

RECEIVER TECHNOLOGY

Geodetic GPS/GLONASS Antenna Measurements

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The IGEX campaign was intended to compare GPS and GLONASS performance and examine the utility of combination solutions. So far, most analysis centers have assumed that the phase centers of the antennas at tracking stations are coincident.

As a portion of our ongoing calibration program for GPS and GLONASS antennas, we have used the anechoic chamber at GSFC to characterize a number of samples of choke ring style geodetic quality antennas at GPS L1 and L2 frequency ranges. We have now extended these measurements to include the GLONASS L1 and L2 and the proposed GPS L3 frequency bands and report on detailed measurements made on one sample of the standard Dorne-Margolin choke ring antennas.

On average, over the entire 1200-1600 MHz L2-to-L1 range, the phase centers of these antennas show frequency-dependent variations with a slope ~-75 microns/MHz (the - sign implying that the phase center at L2 is above that at L1). At the low frequency end covering the GPS+GLONASS L2 frequencies, a slope ~-160 microns/MHz is seen, while around the upper L1 frequency, the slope is ~-50 microns/MHz.

Thus the L2-to-L1 phase center offset is ~26 mm, with the GLONASS phase center ~4 mm below GPS at L2 and ~2 mm below GPS at L1.

We also report on measurements of the effects of antenna radomes, and of the phase center offsets induced by “real-world” mounting piers.

Discussion of Loss of Lock on L1 or L2 Frequency

B. Wiley, *National Imagery and Mapping Agency, St. Louis, MO, USA*

This paper addresses the problem of loss of lock on one of the frequencies when dual frequencies are being observed. This event occurs more often on particular receivers used during the IGEX-98 campaign. Since the orbit computation process requires dual-frequency observations for a period of time, this issue is important. The possible causes of this problem are examined.

NETWORK OPERATIONS

IGEX Activities in Sweden

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Sweden was one of the first countries to establish a multi-purpose permanent national reference GPS network, SWEPOS*. For IGEX-98 four of the 21 stations were equipped with collocated combined GPS/GLONASS receivers, namely dual-frequency Ashtech Z18s at Kiruna and Onsala and single-frequency Ashtech GG24s at Maartsbo and Visby. Data from these four stations are collected by the National Land Survey of Sweden and are transferred to the global data centers for IGEX. For a short time also two Javad receivers where employed in both zero-baseline tests and very short baseline tests at Onsala, plus an additional test with a longer baseline between Onsala and Boraas.

At Onsala, being one of the processing centers of the campaign, data are processed on a daily basis and are assimilated into our own research and will be available within the IGEX campaign. We are currently using, or planning to use the GLONASS results for almost every part of our research, including atmospheric studies (both iono- and troposphere), geodesy, and real time kinematic (RTK) applications. Since we see a potential advantage in using GLONASS we also plan to continue our observations in the future, both for the benefits for ourselves as well as in order to keep supporting IGEX.

We will present our experiences with stations operations, data collecting and handling, and also the results from the data processing.

GLONASS Observation Experience of the Central Research Institute of Geodesy, Aerial Surveying and Cartography in the Frame of IGEX-98

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During January through March 1999 the Central Research Institute of Geodesy, Aerial Surveying and Cartography took part in GLONASS observations at the several Russian permanent stations included in the International Terrestrial Reference Frame (with the exception of one site, Ekaterinburg). Observations were performed by the new combined dual-frequency Javad Legacy GPS/GLONASS receivers, with the precise Regant choke ring antennas. This equipment was loaned to the institute by the Javad Positioning Systems Company. GLONASS/GPS observation data for 165 days were collected and transferred to the BKG data center in Germany. The longest duration of observation was achieved at the Magadan site for 58 days; the shortest occupation was 22 days for Ekaterinburg. Unfortunately there was a large delay in start of observations at these sites due to difficulties in the preparation of custom documents. The institute had difficulties due to the lack of modern computers and reliable Internet communication channels. These difficulties caused the delay in data transfer to the regional data center at BKG. Essential technical help to the institute was given by Javad Positioning Systems personnel. The collected data are now being analyzed. The future activity of the institute is directly related to the financial and economical situation in Russia. The institute hopes for expansion of international communications and for fulfillment of the international projects on mutually advantageous conditions for all directions of geodetic and cartographic activity.

ILRS System Performance in Support of IGEX

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The ILRS IGEX Tracking Campaign began on 19 October 1998 and will continue open ended into the future. The ILRS tracking support of IGEX has been very robust with data obtained on 11 different GLONASS satellites (both day and night) from more than 30 different ILRS stations. The single shot precision ranging to the GLONASS satellites is dependent on the ILRS receiver configuration and the orientation of the satellite array relative to the tracking stations. The only significant problem in support of the IGEX was and still is the numerous GLONASS numbering schemes. In the rest of this paper we will discuss the different tracking phases of the IGEX campaign, the ILRS IGEX tracking network, the ILRS tracking statistics, ILRS data issues, and types of acquisition data products.

The IGEX Data Center at the CDDIS

Carey Noll, NASA Goddard Space Flight Center, Greenbelt, MD, USA; Maurice Dube, Raytheon Information Technology and Scientific Services, Greenbelt, MD, USA

The Crustal Dynamics Data Information System (CDDIS) served as a global data center for the IGEX-98. This paper will present information about the archive and data holdings. Complete listings of data holdings, latency figures, as well as problems encountered during the campaign will also be presented.

LRBA as an Observation Center: Difficulties and Positive Aspects

C. Vigneau, *Laboratoire de Recherches Balistiques et Aerodynamiques, Vernon, France*

The Ballistic and Aerodynamic Research Laboratory (LRBA) was an observation station during the IGEX campaign. The poster deals with difficulties and positive aspects. Difficulties were encountered about data transfer tests during the validation phase and the use of provided software (Hatanaka). The receiver failures have also interrupted the continuous providing of data. Positive aspects were the efficiency of the centralized organization, the support from the international IGEX Network and the ability of a French MOD principal technical center to serve the scientific community.

ORBIT DETERMINATION

GLONASS Orbit Validation by Short-Arc Techniques

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The Russian GLONASS system is based on a concept which has some similarity with the very well known American Global Positioning System (GPS). For a better understanding of this system, several international scientific organizations have proposed an International GLONASS Experiment (IGEX-98). Several centers of the International GPS Service (IGS) performed GLONASS orbit computations simultaneously with GPS orbit computations. Among the objectives of IGEX, the orbit validation by Satellite Laser Ranging data has been considered. Therefore, a laser observation campaign has been organized at the international level in which the Grasse Lunar Laser Ranging has participated.

First analysis of results has been already presented by Springer et al. from the University of Berne. In this paper, we present an analysis based on the laser short-arc techniques developed in Grasse. In this approach, a small translation vector (radial and along-track directions, essentially) of a GLONASS short-arc (less than 10,000 km) is determined by fitting the laser residuals with respect to the GLONASS orbits computed by the IGS centers. The statistical analysis of the laser residuals and of the small translation vectors is performed, as a validation of the GLONASS orbits, exhibiting corrections of a few decimeters. Prospects for the future are given.

Repeatability of Continental Baselines within the IGEX Network

E. Fragner, R.Weber, *University of Technology, Vienna, Austria*

Currently daily orbit solutions, based both on microwave and laser tracking data, are available from five IGEX Analysis Centers (IGEX-AC). These ephemerides are input to the orbit combination process and therefore form the basis of a robust and reliable IGEX product.

The poster describes the results of processing a set of continental baselines and testing the repeatability over a period of several weeks. The calculations are performed by means of the combined GLONASS ephemerides as well as individual IGEX-AC center solutions.

Moreover tracking sites providing single-frequency GLONASS data to the European part of the IGEX network will be connected to the stations mentioned above by introducing ionospheric models calculated by various IGS-AC.

GLONASS Orbit Determination at the Center for Space Research

R.S. Nerem, W. Bamford, R.J. Eanes, K. Key, B.E. Schutz, T. Wynne, *University of Texas at Austin, Austin, TX, USA*

We have computed precise orbits for the GLONASS constellation during the IGEX campaign using two independent types of observations and different software packages: 1) satellite laser ranging (SLR) using our UTOPIA orbit determination software, and 2) radio frequency observations from the IGEX GLONASS tracking network processed using a modified version of the Jet Propulsion Laboratory's GIPSY software. The GIPSY processing used undifferenced carrier phase observations. These results will be presented, along with comparisons to other orbits computed by the IGEX analysis centers. We will also present results on the performance of the Javad receiver we temporarily installed at McDonald Observatory near Fort Davis, Texas during the IGEX campaign.

APPLICATIONS

Static Positioning with GPS/GLONASS

N. Arai, *Electronic Navigation Research Institute, Mitaka Tokyo, Japan*

ENRI (Electronic Navigation Research Institute) has a GPS/GLONASS observation network including one IGEX station and five GPS stations in Japan. We combined following solutions by GLOBK (Global Kalman filter VLBI and GPS analysis program: MIT/SIO) software.

1. ENRI local network solution
2. IGS global network solution by ESA
3. IGEX network solution by ESA

This paper presents the calculation of the combined solution and variations in the baseline's length.

Altimetric Ionospheric Correction Using DORIS and GLONASS Data

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The DORIS precise positioning system [Dorrer et al., 1991] provides dual-frequency Doppler measurements over a global network of about 50 transmitting beacons. These measurements are used to estimate a global map of the vertical Total Electron Content in the ionosphere at the satellite local time [Escudier et al., 1993]. We have applied this technique to measurements obtained with the DORIS receiver flying on board the TOPEX/Poseidon satellite. It is used on an operational basis for the ionospheric correction to be applied to the Poseidon single-frequency altimeter and for the calibration of the ionospheric content derived from the TOPEX dual-frequency radar altimeter. Comparisons between the TOPEX and the DORIS data set over the whole mission (from 1992 to mid-1999) will be presented. New development of the assimilation chain will allow us to use the GLONASS data to obtain a better coverage and time sampling. This source of correction should be used in the future as an alternative source of correction for complementary mission based on single-frequency radar altimeters.

Analytical Solar Radiation Pressure Model for GLONASS: Algorithm and Initial Results

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Solar radiation pressure (SRP) is a significant perturbing acceleration on the GLONASS orbit. Although the effects of SRP on an orbit can be estimated empirically with great precision for highly redundant solutions, analytical models are useful for reducing the number of parameters in a solution, and for data processing where fewer observations are available. However, accurate analytical models can be difficult to compute for spacecraft of complex shape, such as the GLONASS IIv satellite. This is principally due to the effects of spacecraft components shadowing each other, and because of secular and other periodic variations, possibly due to attitude control limitations and weathering of the spacecraft materials. This paper discusses a new approach to computing analytical SRP models. The photon flux is simulated using a pixel array. The illumination of the spacecraft and subsequent reflection of the light is calculated using ray tracing algorithms. The summed accelerations are decomposed along the spacecraft X and Z axes for each Earth-probe-Sun angle, and a Fourier series is fitted to the data points to form the model, in a similar fashion to the GPS ROCK models. The resulting model is tested by numerical integration of the spacecraft dynamic model, using a truncated Earth gravity field, as well as solar and lunar gravity. IGEX-98 precise orbit data is used for initial conditions and for analysis of residuals. The software allows the spacecraft to be perturbed from its nominal attitude to simulate Y-bias and the magnitude of scaling factors for the modeled acceleration along the X and Z axes. The initial results for models and testing are presented.